The Cartesian Diver as an Aid for Teaching Respiratory Physiology

Greg K. Fitch, Ph.D.

Associate Professor of Biology
Department of Biology
Avila University
11901 Wornall
Kansas City MO 64145
E-mail: fitchgk@mail.avila.edu

ABSTRACT: The mechanism by which air enters the mammalian lung is difficult for many students of physiology. In particular, some students have trouble seeing how pressure can be transmitted through a fluid such as the intrapleural fluid and how the magnitude of that pressure can change. A Cartesian diver, an old-time child's toy, may be used as a visual aid during lecture to illustrate and make more understandable these hard-to-grasp concepts. The Cartesian diver is easy to construct from readily available materials. In addition to helping explain lung mechanics, the performance of the Cartesian diver takes most students completely by surprise and thereby serves to "wake up" the student whose mind may not be completely engaged in the topic.

KEYWORDS: physiology, respiration, visual aid, Cartesian diver

INTRODUCTION

Visual aids add spice to lectures. A visual aid is even more useful when, in addition to adding flair, it makes more understandable an otherwise abstract concept. Used properly, the Cartesian diver, an old-time child's toy, can be such an aid.

A Cartesian diver, also known as a Cartesian devil or bottle imp, is described in Webster's Dictionary (1983) as "a simple hydrostatic toy consisting of a hollow figure partly filled with air that may be induced to float at various depths in a tube of water by compression of the air." The basis of the toy's operation is that although air is normally thought of as being "light," it can be made more dense if the mean distance between the molecules is decreased by compression. In a Cartesian diver, increases and decreases in air compression and density are achieved by increasing or decreasing pressure in the fluid surrounding the air. *Because increases and decreases in fluid pressure (of the intrapleural fluid) are important in deflating and inflating the mammalian lung, the Cartesian diver can be used as a model for these aspects of lung function*.

I was prompted to bring a Cartesian diver into my classroom following a discussion of the mechanics of lung ventilation with my upper-level Human Physiology students. To facilitate understanding, many textbooks and lecturers divide the smooth, integrated process of inspiration into a series of separate steps (for example, see Stalheim-Smith and Fitch, 1993). In this stepwise description, the inspiratory muscles first contract. This muscular contraction moves the wall of the thoracic cage and its attached layer of parietal pleura away from the layer of visceral pleura that is attached to the lung wall. Because the parietal and visceral regions of the pleural membrane are continuous (much like the "front" and "back" walls of a balloon), the size of the pleural cavity bounded by the pleural membrane is increased as the walls of this cavity are pulled away from one another (Figure 1).

At this point in the lecture, I usually ask students to recall from introductory physics what happens to the pressure exerted by a population of molecules when the volume they occupy is made larger. Many students are able to answer that such a change will decrease the pressure exerted by the molecules. (This relationship is described by Boyle's Law.) I then return to the stepwise description of inspiration, pointing out that an increase in the size of the pleural cavity causes the

pressure (called intrapleural pressure) within the cavity to drop, creating in essence a partial vacuum around the lung. Because intrapleural pressure at all times "pushes" on the outer lung wall at the same time as atmospheric/intrapulmonary pressure pushes on the inner lung wall in the opposite direction, a decrease in intrapleural pressure (a weaker push) allows the push exerted by intrapulmonary pressure to move the lung wall outward, thereby expanding the lung. Stated differently, the elastic lung expands as it is sucked "into" the partial vacuum that has been created around it. This increase in lung size then causes the intrapulmonary pressure within the lung to fall, and atmospheric air flows from a region of higher pressure (the atmosphere) to a region of lower pressure (within the alveoli), filling the lung. The lung does not expand because air has entered it; rather, air enters the lung because it has expanded.

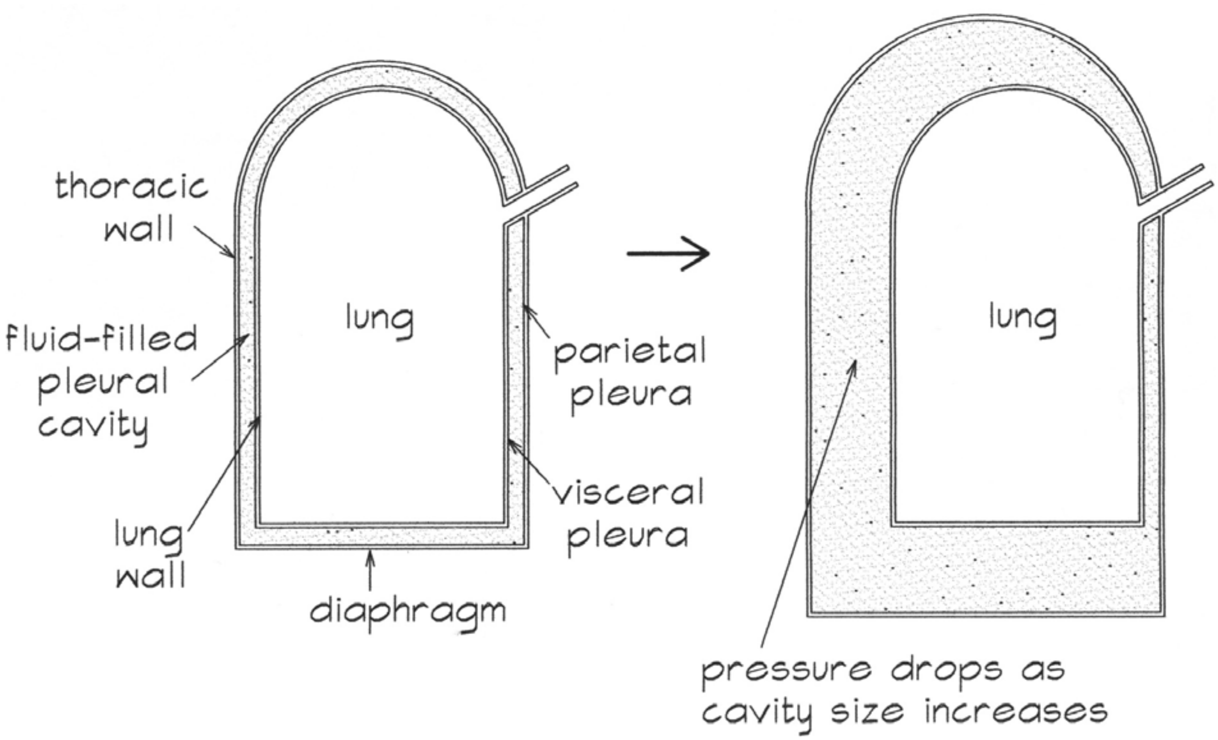

***Figure 1**. Volume and pressure changes occurring in the human pleural cavity when inspiration is viewed as a stepwise process. Before contraction of the inspiratory muscles, the pleural cavity in a normal individual assumes its smallest volume (left). As the inspiratory muscles contract, the layer of parietal pleura attached to the thoracic wall is pulled away from the layer of visceral pleura attached to the lung wall, thereby increasing the volume of the pleural cavity (right). Boyle's Law states that this increase in intrapleural volume leads to a decrease in intrapleural pressure. The lung expands as its walls move in the direction of this decreased intrapleural pressure. Note that the parietal and visceral layers of the pleura are both part of a single, continuous membrane.*

Several semesters ago, a bright student objected to one portion of the above description. Essentially this student stated that while he agreed that increasing the volume of the container occupied by a population of *gas* molecules would decrease the pressure they exert, he had been taught in physics that liquids are incompressible and thus did not see how the same argument could be applied to a population of molecules forming a liquid. His position was that the volume of a liquid remains constant, meaning that if molecules were not added to or subtracted from the intrapleural fluid, its volume (and thus, according to Boyle's Law, its pressure) could not change. The change in the magnitude of the pressure gradient across the lung wall that I had described therefore could not be accomplished.

I tried to address this objection, but could tell that the class found my answer neither clear nor satisfying. Later that day, I decided to build a Cartesian diver and bring it to the next meeting of the class. I have used it as a visual aid during lectures on the mechanics of ventilation in every subsequent semester.

BUILDING A CARTESIAN DIVER

Most science teachers will find that they already have the materials needed to construct a Cartesian diver. Required materials include an empty plastic soda pop bottle (sizes from sixteen ounce to two liter all work fine), the screw-on lid for the soda pop bottle, and a small glass test tube. Optional materials include a glass Pasteur pipette with rubber bulb and a Bunsen or alcohol burner. Fill the plastic soda pop bottle to the very top with water. Next, fill the test tube about half full of water, quickly invert it without losing the water, and push it into the water within the plastic soda pop bottle so that the open mouth of the test tube faces the bottom of the soda pop bottle. The test tube should float (by virtue of its being half-filled with air) in the water at the top of the soda pop bottle with the rounded bottom of the test tube upward. Now screw on the lid of the soda pop bottle, trapping the floating test tube inside. The rounded, closed bottom of the test tube will be pushing up against the screwed-on lid (Figure 2). If your test tube is at the bottom of the plastic bottle instead of floating, you do not have enough air trapped inside the test tube. Remove the test tube and try again.

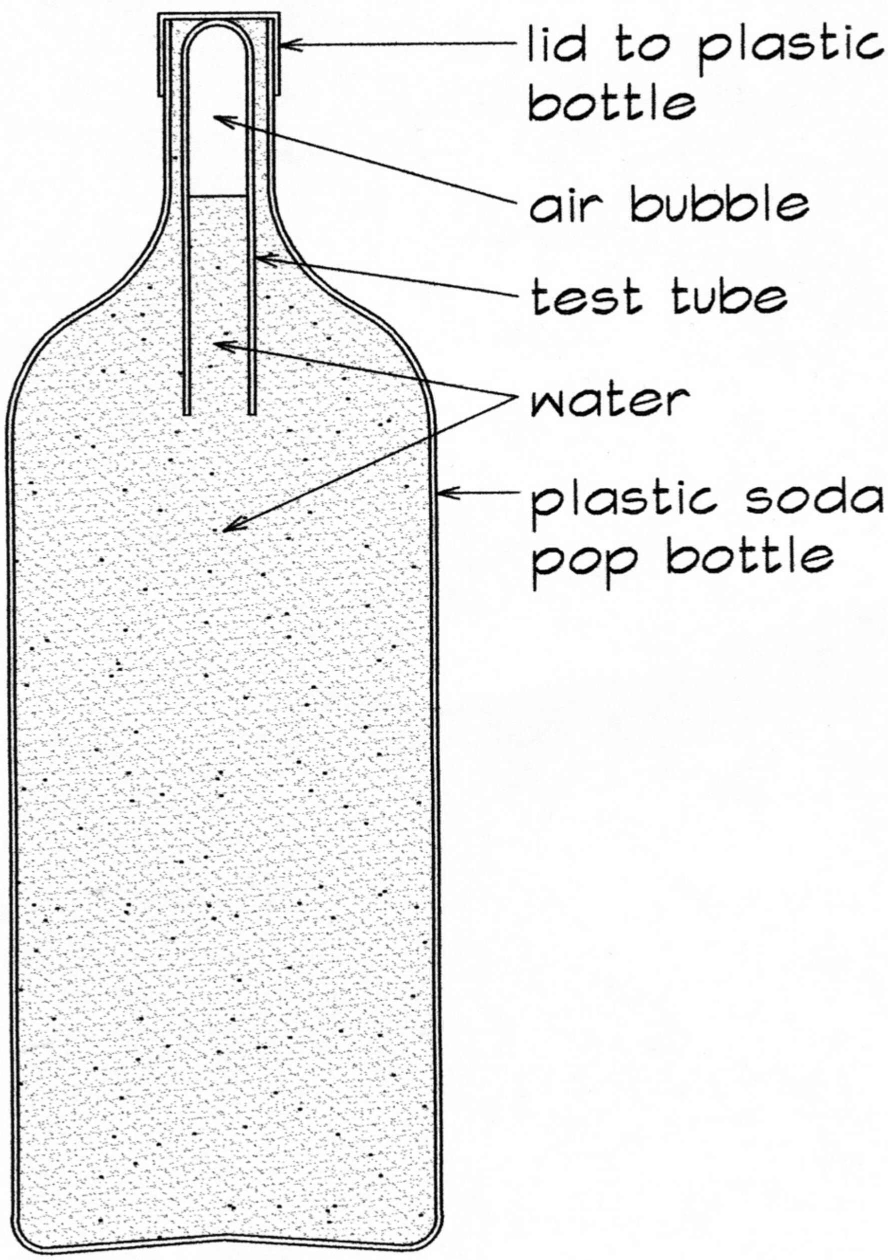

***Figure 2**. Cartesian diver constructed from a plastic soda pop bottle and a test tube. An air bubble is trapped within the inverted test tube, causing it to float against the lid of the plastic bottle.*

The tricky part of Cartesian diver construction is getting the correct amount of air in the test tube. Using both hands, firmly squeeze the sides of the soda pop bottle. Does the test tube sink or "dive" to the bottom? If it does, you are set. If it does not, you need to remove some air from the test tube. One way to adjust the amount of air in the test tube is to remove and then reinsert it, using trial and error to get the desired amount of air. A more controlled method for adding or removing air involves the use of a bent Pasteur pipette. To bend a pipette, hold the middle portion of the narrow, drawn-out end of the pipette horizontally in the flame of a Bunsen or alcohol burner. When the glass becomes hot enough, the tip of the drawn-out part of the pipette will "droop" down, giving you roughly a 90 degree bend in the glass. You then need to rotate the pipette along its long axis while still heating it so that this bend increases to almost 180 degrees. The bend must be sharp enough so that the entire bent end of the pipette will fit into the mouth of the soda pop bottle. And the length of pipette beyond the bend must be great enough to extend part way into the air in the test tube. The bent pipette can now be used to adjust the air level in the test tube. After each adjustment, screw the lid back onto the soda pop bottle and squeeze its sides as before. When you can get the test tube to dive to the bottom with a squeeze of moderate strength, your Cartesian diver is completed.

HOW THE CARTESIAN DIVER WORKS

The real value of the Cartesian diver to a teacher of respiratory physiology is that it shows that (1) pressure can be transmitted through a fluid, and (2) the strength of that pressure can change. The water in the soda pop bottle exerts a hydrostatic (fluid) pressure against the walls of its container. You can easily convince students of this fact by asking what would happen if you used a needle to make a small hole in the side of the soda pop bottle. It is intellectually valid to think about this pressure as being transmitted throughout the entire volume of fluid. The magnitude of the pressure is equal at all points at a given horizontal level of the bottle, although due to gravity it is slightly greater at the bottom of the bottle than at the top. The key point illustrated by the Cartesian diver is that the magnitude of the pressure transmitted through the fluid can be increased. Squeezing the sides of the soda pop bottle causes such an increase. Ask students to watch the column of air within the test tube as you slowly squeeze the soda pop bottle. It is easy to see that the height of the air column progressively decreases before the test tube begins to dive. The explanation for the shortening of the air column is that squeezing the soda pop bottle increases the pressure exerted by the fluid in all directions, including in the upward direction of the air-water interface. As this increasing pressure "pushes" on the air, the gas molecules forming it are forced closer and closer together. As the gas molecules get closer together, the column of air becomes shorter and the density of the air increases. (Air becomes "thinner" as one drives up a mountain for the opposite reason; the decreasing height and thus decreasing weight of the column of air "sitting" on the earth's surface exerts a weaker push on the gas molecules near the earth's surface, allowing these molecules to be farther apart than they would be if they were under a taller column of air.) An increase in the density of gas molecules within the test tube shortens the column of air, thereby allowing water to enter the test tube. These changes increase the mean density of the test tube plus its contents. When the mean density of the test tube and the water and air within it becomes greater than the density of the water in the soda pop bottle, the test tube sinks.

Your students may ask *how* squeezing the soda pop bottle increases the pressure transmitted through the water it contains. Although the complete answer to this question is best left to a physicist, the main point is that while a liquid is incompressible on a macroscopic scale, applying pressure to the liquid does compress it by a very small amount. By squeezing the plastic bottle, you are forcing the water molecules to move slightly closer to one another.

USING THE CARTESIAN DIVER AS A LECTURE AID

After I use the Cartesian diver to demonstrate how the pressure transmitted through a fluid can change, I next use it as a model for human inspiration. In small classes, I typically use the diver once or twice to model inspiration and expiration, and then ask the students to pass the diver around the room and squeeze it for themselves.

As a model for human inspiration, the walls and bottom of the soda pop bottle represent the right (or left) pleural membrane. The space within the bottle is analogous to the pleural cavity, and the water within this space represents intrapleural fluid. One aspect of this model of inspiration is a bit counterintuitive: contraction of one's arm muscles to squeeze the soda pop bottle represents *relaxation* of the muscles of inspiration (the diaphragm and external intercostal muscles). Thus, to demonstrate inspiration with the model, you must *release* the soda pop bottle that you were previously holding in the squeezed position.

I usually show the model in the following manner. Before beginning any explanation, I squeeze the plastic bottle to sink the test tube. Holding the diver in the squeezed position, I point out that we are now "between" breaths--that is, between the end of expiration and the onset of the next inspiration. At this point, because the inspiratory muscles are relaxed, the pleural cavity assumes its smallest volume during the respiratory cycle. Likewise, the soda pop bottle is assuming its smallest volume (because I am pushing inward on its walls). I then tell the class that I am

about to release my squeeze on the plastic bottle, which will represent contraction of the inspiratory muscles. Just as contraction of those muscles moves the chest wall and attached parietal pleura outward (and diaphragm downward), releasing the soda pop bottle allows its walls to move outward. The "pleural cavity" (soda pop bottle) is about to increase in size.

As I release my squeeze on the soda pop bottle, I point out that the pressure in the "intrapleural fluid" (water within the soda pop bottle) is now decreasing. In the Cartesian diver, this decreased pressure allows the gas within the test tube to expand and the test tube to float once again. In the mammalian body, the decreased pressure within the intrapleural fluid forces the lung wall toward the wall of the thoracic cage--that is, makes the lung expand. The expansion in turn causes atmospheric air to be pushed into the alveoli where the pressure has become slightly less than atmospheric pressure. This pushing of air into the alveoli completes the process of inspiration.

Several caveats are in order here. If you are describing mammalian lungs in general rather than human lungs in particular, the space within the soda pop bottle represents for some species the combined right and left pleural cavities as the two cavities communicate with each other. (In humans they do not communicate.) Also, the model and the above description do not give a complete description of the mechanics of inspiration. Ignored, for example, is the attraction between parietal pleura and visceral pleura due to the layer of water between the two. This attraction aids lung expansion as the moving chest wall attempts to pull the two pleural layers apart. The above description also ignores the elastic force inherent in lung tissue, which "attempts" to reduce lung size during the periods of both inspiration and expiration (Stalheim-Smith and Fitch, 1993). Finally, as mentioned earlier, the wall of the thoracic cage, the pleural membrane, and the lung wall move together at almost exactly the same time, rather than in the stepwise fashion in which they were described above. Despite these caveats, the Cartesian diver nicely illustrates certain aspects of lung ventilation and, in addition, is guaranteed to wake up (at least temporarily) even the sleepiest student.

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